

Keywords: *Aviation Maintenance, Radio-Frequency Identification (RFID), Item-Unique Identification (IUID), Scheduled Removal Component (SRC)*

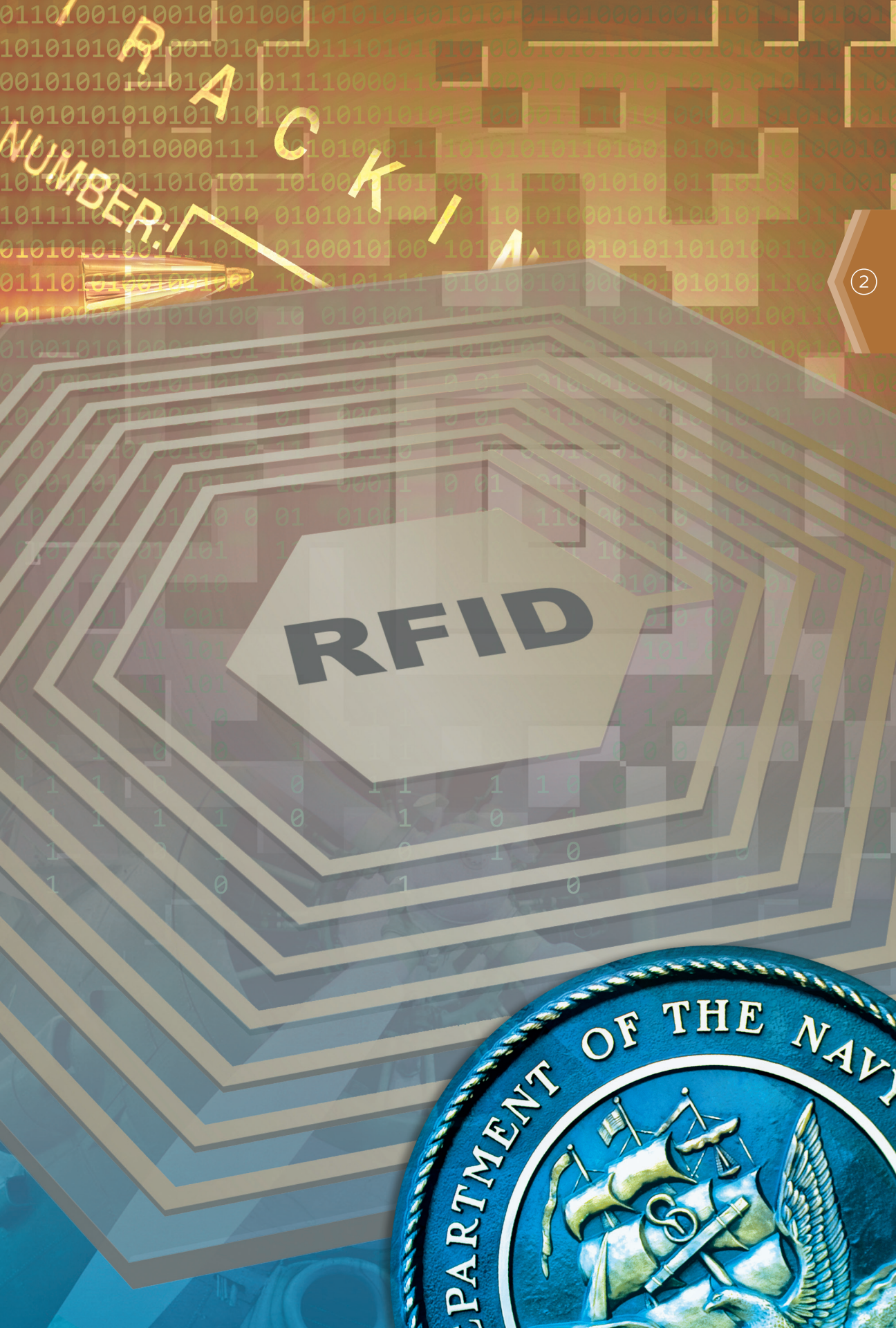


Managing Life-Cycle Information of Aircraft Components

 *Geraldo Ferrer and Aruna U. Apte*

When an aircraft component needs replacement of a serially controlled item, a maintenance officer in the U.S. Navy uses the Scheduled Removal Component (SRC) card to confirm the component's life cycle, to verify that the part is ready-for-issue, and to verify how many flight-hours it still has left. Unfortunately, replacement components are often missing the SRC cards. Further, when the cards are received simultaneously with the aircraft component requiring replacement, their encoded data are unreliable, which then precludes the part from being immediately installed. In this article, the authors analyze the impact of current paper-based life-cycle management of serially controlled parts, and investigate item-unique identification and radio-frequency identification technologies as alternative ways of tracking these parts to increase operational availability.

Report Documentation Page			Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.				
1. REPORT DATE APR 2012		2. REPORT TYPE		3. DATES COVERED 00-00-2012 to 00-00-2012
4. TITLE AND SUBTITLE Managing Life-Cycle Information of Aircraft Components			5a. CONTRACT NUMBER	
			5b. GRANT NUMBER	
			5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)			5d. PROJECT NUMBER	
			5e. TASK NUMBER	
			5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Defense Acquisition University Press,Fort Belvoir,VA,22060			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)	
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited				
13. SUPPLEMENTARY NOTES See also ADA560104, Defense Acquisition Research Journal, April 2012, Vol 19, No 2, Issue 62				
14. ABSTRACT When an aircraft component needs replacement of a serially controlled item, a maintenance officer in the U.S. Navy uses the Scheduled Removal Component (SRC) card to confirm the component's life cycle, to verify that the part is ready-for-issue, and to verify how many flight-hours it still has left. Unfortunately, replacement components are often missing the SRC cards. Further,when the cards are received simultaneously with the aircraft component requiring replacement, their encoded data are unreliable, which then precludes the part from being immediately installed. In this article, the authors analyze the impact of current paper-based life-cycle management of serially controlled parts, and investigate item-unique identification and radio-frequency identification technologies as alternative ways of tracking these parts to increase operational availability.				
15. SUBJECT TERMS				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 23
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified		



PACK NUMBER: 1

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Before a plane in the Department of Defense inventory leaves the runway or carrier and is lifted in the air, it must first be put through rigorous aircraft engine maintenance. None would argue with this premise. The Aviation community, as with many other communities across the Department of Defense, is continually studying how to make the process better, faster, and cheaper, without sacrificing one scintilla of maintenance excellence and safety.

Recently, a study was published that addressed aircraft engine maintenance, demonstrating that improved operations and cost savings could be realized by rationalizing the supply network for aircraft engine maintenance in the U.S. Air Force (Ferrer, 2010). That study analyzed demand data for the Pratt & Whitney and the General Electric spare engines used in the F-16 Fighting Falcon, and concluded that pooling the inventories of Air Force bases within operationally acceptable distances would enable substantial reduction of nationwide safety stock levels. For purposes of this study, we expanded the inventory management analysis, which was originally focused on complete aircraft engines, to consider the management of individual parts throughout their life cycles and the impact of certain organizational decisions on maintenance operations.

Over the lifespan of an aircraft, specific parts are installed, removed, and replaced during a variety of maintenance procedures. When a component is removed from an aircraft, custody and ownership rights generally transfer at both intraorganizational and interorganizational levels. Because some parts are critical to flight safety, they have strictly specified life-cycle maintenance requirements that must be accurately executed, tracked, and logged. To properly service these components, technicians need information about individual parts such as the hours flown, maintenance history, and inspection data. The process of logging and tracking maintenance parts is extremely beneficial for improving readiness.

For situations in which multiple entities provide maintenance to aircraft components, at potentially different locations, the need for readily accessible maintenance history makes it necessary to keep an efficient information system. Ultimately, life-cycle management processes for military aircraft components should strive to ensure the highest levels of safety, operational availability, and squadron readiness. However, logging data using a paper-based system is labor-intensive and error-prone.



To ensure high performance of maintenance processes, many civilian and military aviation organizations are starting to implement Product Life Cycle Management (PLM), a closed-loop system that encompasses internationally standardized data-exchange technology to manage part information from cradle to grave. These tracking databases serve two important purposes. First, they serve as a part life-cycle data library, where the service technician can find the history of maintenance events. Second, engineers can examine historical part performance data to refine current preventive-maintenance practices and to minimize or prevent unexpected and catastrophic part failures.

We propose the combined use of two automated information technologies such as Radio-Frequency Identification (RFID) and two-dimensional Unique Item Identification (UID) to enhance life-cycle tracking capability for aircraft operators. The objective is that, upon accessing unique identification attributes (part number, serial number, and manufacturer's code), the maintenance technician should be able to access expended flight time, maintenance, and inspection data of critical parts. By logging a part's flight-hours, maintenance, and repair events in a centralized database, aircraft operators would reduce the cost of tracking and maintaining service history. It would also reduce the time to solve in-service problems by improving the accuracy of information exchanged between customers and suppliers. The ability to easily reference and update a part's maintenance history is expected to facilitate accurate configuration control and repair history, support accurate and efficient spare-parts pooling, and improve identification of rogue parts.

However, the use of RFID technology alone may not be sufficient to track a part throughout its life. RFID technology has been implemented in many military supply chain applications (DoD, 2009), but life-cycle tracking of valuable assets has been slow to incorporate advanced technologies. Similar to civilian aircraft, military aircraft have much to gain from the use of tracking technologies in support of a PLM system. To investigate how efficiencies can be attained in the logistics of aircraft engine maintenance, this research focuses on the U.S. Navy's cradle-to-grave aviation part life-cycle process.

An Approach for Component Tracking: SRC Cards and NALCOMIS

The current process uses Scheduled Removal Component (SRC) cards, which we adopted as the benchmark method. We also considered the procedures used by the Naval Aviation Logistics Command in its Naval Aviation Logistics Command Operating Maintenance Information System (NALCOMIS) to track serially controlled components (Staffieri, Holsti, & Gray, 2009). Our concerns focused on the loss of critical part history information, and the errors incorporated in the component's life-cycle information. We highlight the problems associated with the use of SRC cards and propose an approach for their gradual discontinuation. We show that an important facet of aviation maintenance would enjoy time and money savings due to decreased workloads if the correct type of tracking technology configuration is employed. Although the study centers on the Navy's F/A-18 Hornet community and its interaction with the Configuration Management Information System/Aeronautical Time Cycle Management (CMIS/ATCM) program repository, the analysis and recommendations can be applied to any aircraft that has its serially controlled components tracked by SRC cards or any other manual process.

Consider the F414-GE-400 engine, the power plant used in the F-18 Super Hornets and the E-18 Growler. The Navy plans to purchase 85 Growlers to replace the aging fleet of E-6 Prowlers. The aircraft requires two of these engines, and each engine has a modular design. The maintenance operation is initiated at the Fleet Readiness Center at Naval Air Station in Lemoore, CA, where engine modules are removed from the aircraft and replaced, unless the engine is repaired onboard a carrier's Aircraft Intermediate Maintenance Department.

Several parts installed on the F-18 Hornet require life-cycle tracking. Throughout the life of the aircraft, multiple components are removed, replaced, and repaired for reuse in the same or in another aircraft. Engineering specifications driven by safety requirements indicate that these components must be serially managed, i.e., they should be uniquely tracked, controlled, or managed in maintenance, repair, and supply by means of their serial numbers.

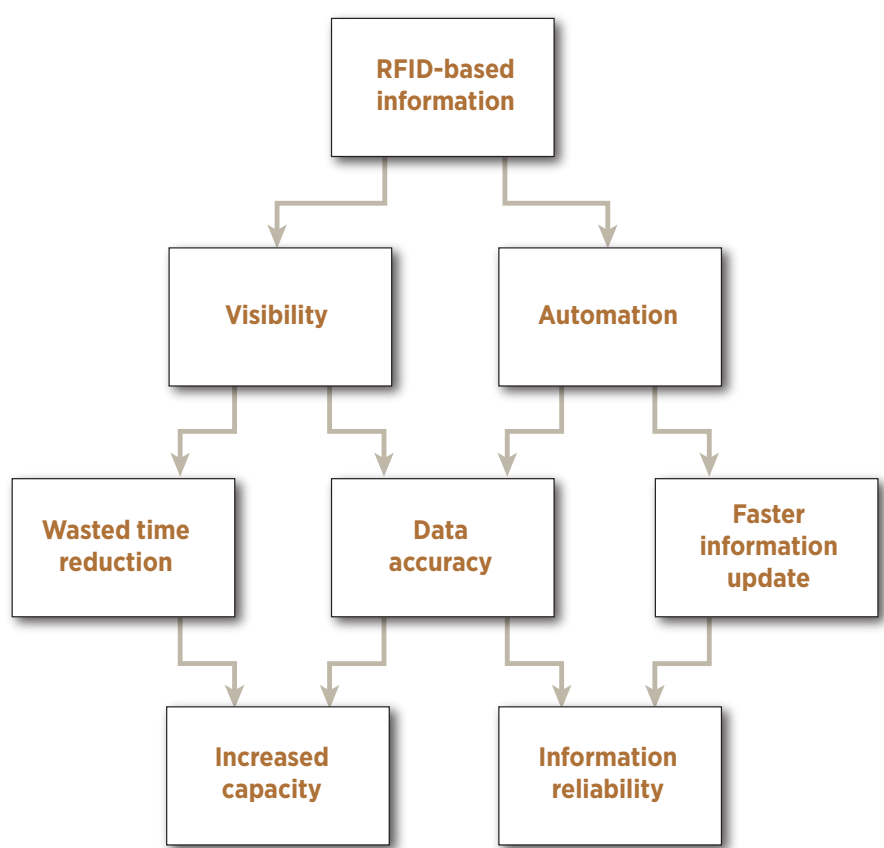
The NALCOMIS is the information system used to track and manage aircraft maintenance and material data throughout all Navy squadrons. NALCOMIS tracks expended flight-hours and completed maintenance actions over a part's lifetime as it exchanges hands from one command to another using an SRC card for each serially managed part. Squadron maintenance personnel primarily use this database for day-to-day management of aircraft maintenance. It can also generate many different types of maintenance reports that support tracking and planning current and future aircraft maintenance requirements. The reports also provide means to collect statistical data that can lead to the identification of high-failure parts or maintenance practices. However, NALCOMIS is not integrated with any online information network; it does not have the ability to generate an electronic card to other commands or databases, so maintenance administrators must ensure that an accurate SRC card physically accompanies each part in use or stored as spare.

The installation of a new serially controlled part in an aircraft is the event that originates the SRC card. Maintaining physical custody of the SRC card and documenting life-cycle history updates on the SRC card are the responsibility of the squadron's Logs and Records personnel. The controlled item is removed as the result of component failure or required periodic maintenance, at which point the card is retrieved and updated.

The complete maintenance history, installation, and usage data for all items designated as SRCs are recorded on the SRC card. The cards are thorough and unambiguous. They are kept as part of the aircraft logbook or the aeronautical equipment service record as long as the component is installed. When the component is removed from the aircraft or equipment, the SRC card accompanies it through the supply chain. Updated and maintained on file by a maintenance administrator, an SRC card alone can have a direct impact on squadron readiness.

Occasionally, component paperwork is mishandled, particularly aboard ship. Spare parts arrive and are unpacked, and, many times, the documentation that comes with them is lost in the heat of the moment. If an SRC card is not present, or it does not have adequate information, an investigation takes place to recreate a new card with reliable history information. This effort takes time and delays the component’s availability. The Appendix to this article describes the process followed when a worn part and its card are removed for repair.

FIGURE 1: PROCESS FLOWCHART FOR SERIALLY MANAGED PARTS CONTROLLED WITH SRC CARDS





One could praise the process as being conservative because it is prepared to handle exceptions such as inventory shortage (Appendix, step 4) or missing cards (step 5). However, these exceptions happen quite often, and their prominence indicates serious deficiencies in the management of serially controlled items by the U.S. Navy, leading to many instances where the squadron is faced with decreased readiness levels when many aircraft are certified as unfit to fly.

TABLE 1: COMPARISON BETWEEN RFID AND UID IMPLEMENTATION INITIATIVES

	RFID	IUID
Tagging level	Package or container	Item
Technology	UHF RF with EPC encoding	2D Data Matrix ECC200
Purpose	In-transit visibility	Life-cycle visibility
Target items	Shipment to distribution center Certain classes of supply	Serially controlled items Item value > \$5000
Initial implementation	1 Jan 05	1 Jan 04

Improving this process is a priority for the aviation community, and it can be achieved with a redesign that includes the use of automated tracking technologies. Table 1 compares two initiatives in the Department of Defense: item-unique identification (IUID) and RFID. Both technologies have been considered as candidates for managing DoD-owned assets. We discuss them in the context of life-cycle maintenance management.

Tracking Technologies

RFID Technology

RFID has been widely used in military supply chain applications. It is expected to receive widespread adoption, considering its many benefits. For example, using RFID tags to automate the receiving operation can reduce labor costs, enhance accuracy, and increase inventory turnaround by decreasing the amount of time that an item spends in a distribution center. Using RFID in a job shop environment may also

enhance tracking of high-priority items and substantially reduce cycle time for part repair/replacement (Hozak & Hill, 2010; Wang, He, & Kong, 2010; Ferrer, Heath, & Dew, 2011).

RFID technology supports the information flow in the supply chain by increasing visibility, facilitating the automation of processes, and providing greater data accuracy, as shown in Figure 1. Visibility is the ability to retrieve inventory information, as needed. Automation is the ability to update changes in inventory information as they happen, without the need for manual data entry, keeping the database up-to-date. Visibility helps reduce wasted time when a misplaced part or item needs to be located in a large inventory. Combined, automation and visibility provide data accuracy. These benefits increase process capacity and reliability (Ferrer, Dew, & Apte, 2010).

FIGURE 2: BENEFITS DERIVED FROM USING RFID IN LIFE-CYCLE TRACKING



During maintenance activities, faster information flow results in less time and effort to record component movement in the repair shop. Better visibility and faster information flow lead to faster processes, helping managers in their decision-making process and helping users of the system to access reliable information. With increased capacity, labor requirement is reduced in both the receiving and delivery points responsible for identifying, counting, locating, documenting, and managing the movements of components. Automated documentation benefits the maintenance process by helping the technician to use accurate information about the component's life cycle every time.

Moving from a familiar and trusted process to a new process using untested technology is a very uncomfortable decision for managers. There is substantial resistance to change in most organizations, even when the change brings a promise of exceptional returns. Many manufacturing facilities and distribution centers have been using barcode systems for tracking materials for years, rendering this technology mature, efficient, and familiar. Consequently, it is difficult to make the case for any other tracking technology that requires substantial investment. Likewise, an SRC card is a tried-and-tested approach for managing serially controlled components. As a result, resistance to change is one of the greatest challenges preventing the adoption of RFID or any other technology. If the cards are kept with the components at all times, and information is entered accurately, then it serves the information needs of the maintenance process. However, there are too many "ifs" that make this process unreliable, so advanced technologies must be considered, and managers must make a concerted effort to change.

Despite potential benefits, RFID technology is not fully mature, and has some limitations. The physical properties of the materials that require tracking as well as their surroundings can affect the reliability of readers. For example, liquids absorb radio frequency signals, while metals reflect them. In particular, many aviation components are made of dense materials that raise difficulties for an RF-based control system. Navy ships and depots have a multitude of equipment and surfaces that are made of steel and other materials that reflect RF signals. External factors, including noise from nearby electric motors, can impact its performance. Further, there is great concern that spurious RF signals may affect or trigger antiquated electric systems aboard military ships, with potentially disastrous consequences. Consequently, the adoption of RFID technologies to track serially controlled items requires careful planning and design.

IUID System

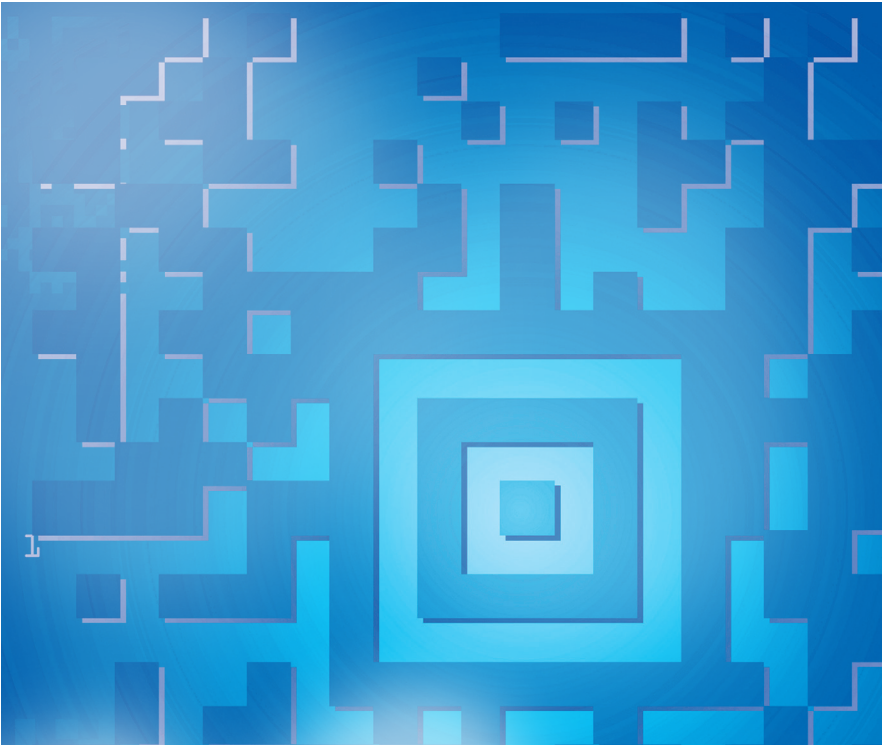
IUID is an asset identification system instituted by the U.S. Department of Defense (DoD) to uniquely identify discrete, tangible items and distinguish each of them from other identical items owned by the DoD. The identification takes the shape of a machine-readable, two-dimensional optical code using the Data Matrix ECC200 standard (DoD, 2004). UID is formatted in accordance with specified standards (MIL-STD-130). The Data Matrix ECC200 symbol has a checkerboard appearance, with each uniformly spaced, square-shaped cell corresponding to a data bit. The symbol is constructed as a combination of light and dark elements that must all be read before any characters can be recognized (Drews, 2009). The formatted data is called a Unique Item Identifier (UII). Once assigned to an item, the UII is never changed, even if the item is modified or refurbished. Like an automobile license plate, or a social security number, someone reading the UII itself will not be able to learn much about the current state of the item. A UID reader is able to recognize just the unique characters marking the item, and identify it from other similar items in the system. The main benefit is to provide a permanent identification to each individual part and use that information in many applications:

Virtually all UID data are stored offline, which provides many benefits. To retrieve information about the item with the UID mark, the user needs to access a central database, the IUID Registry, and learn permanent data elements associated with the mark. Most of this baseline data is static; it is never changed during the item's lifetime, except to record its permanent retirement (DoD 2005).

The Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics mandated the use of UID for all solicitations on or after January 1, 2004, for equipment, major modifications, and spare parts. A unique identifier is exclusively designated for each particular part, which is then registered in the IUID Registry. Each vendor that does business with the DoD has to obtain a UID number from the master database to ensure that no part in the DoD can be mistaken for another part. As the number of vendors for common aircraft parts increases, part and serial numbers may accidentally be duplicated on different components. This can result in the ordering of an incorrect part based on correct part numbers. IUID eliminates this problem. The fundamental benefit of this policy is that the UID is a permanent marking for serially managed items and the perfect life-cycle tracking enabler.

IUID Registry

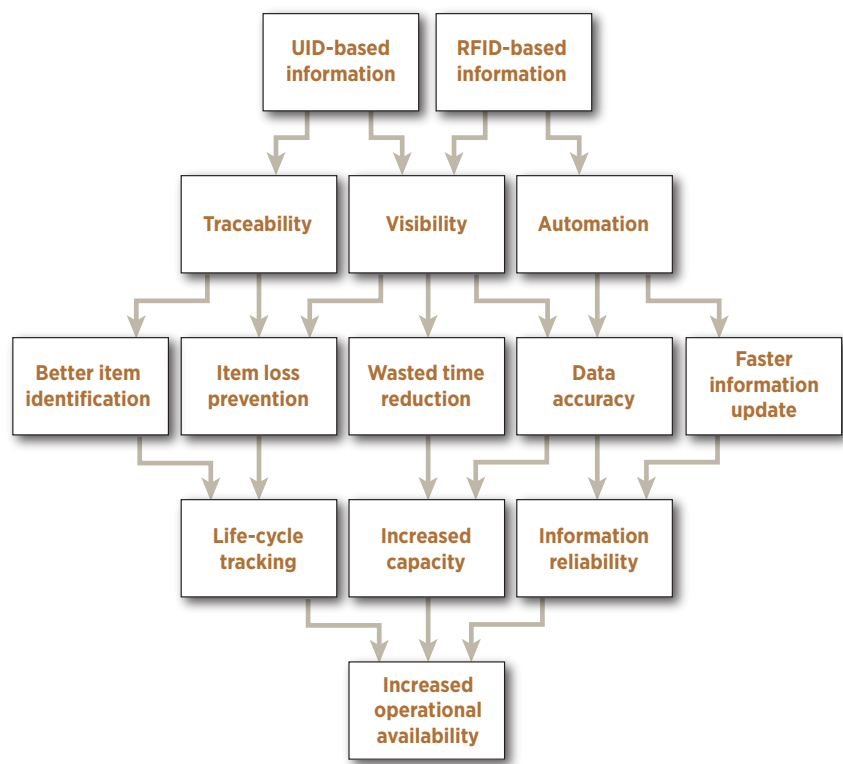
The IUID Registry is the ultimate repository where all IUID data are captured. Updates are limited to change of custodianship and item retirement. The registry is neither intended nor designed to be a working database for individual programs. In fact, the registry itself does not perform any value-adding activity. Rather, its purpose is to serve as an anchor to other information systems used for life-cycle product management, such as maintenance management systems, property management systems, and other systems that may or may not yet exist. Historically,



we observed similar experience with the development of new uses for the Social Security Number in the United States, which was originally created to track retirement contributions and benefits of individuals, and is now used in a variety of private and governmental information systems to manage tax, banking, insurance, medical and employment records, education records, credit worthiness, etc. Likewise, it is expected that other benefits could be derived from uniquely identifying valuable and critical assets with IUID.

Figure 2 shows how the use of information coupled with the help of unique identifiers can enhance life-cycle tracking. Traceability is the ability to store asset information as it undergoes multiple events in its life cycle. Visibility is the ability to retrieve location information, as needed, which can be obtained with correct registration of UIDs in the IUID Registry. Combined, visibility and traceability ensure accurate item identification and the reduction of item losses—important requirements for life-cycle tracking.

FIGURE 3: BENEFITS DERIVED FROM USING UID IN LIFE-CYCLE TRACKING



Analysis

The adoption of RFID, IUID, or any other automated tracking technology for serially managed items in the naval aviation community is proceeding at a very slow pace. However, based on anecdotal conversa-

tions with officers in a variety of maintenance positions in the military services, this situation seems to be the norm, not the exception. That is, a manual control, similar to SRC cards, remains the principal mode of managing serially managed items. A survey of experienced maintenance officers found that missing SRC cards is a rather frequent event, with significant impact in the operational availability of assets (Staffieri et al., 2009). That study estimates that, by forcing early retirement of potentially good parts, each lost card results in a loss of \$75k, on average.

As the flowchart in the Appendix indicates, a missing card leads the squadron to contact customer service at the CMIS/ATCM repository. The CMIS is in charge of keeping accurate data on serially managed component usage, based on a manual process using copies of the SRC cards that it receives every time a used component is removed from the aircraft, or when an RFI component is installed. If the card is missing or is inconsistent with the part, the CMIS can indicate the last time that particular part was installed. Using that information, it can then estimate the number of hours remaining in that part. In practice, that estimation is difficult to execute, and arbitrary flight-hour penalties are imposed on those components, reducing their value and accelerating their retirement.

During the 6-month period from October 2008 to March 2009, in the process of manually maintaining their database, ATCM received cards corresponding to 17,318 component replacements, an average of 140 cards per business day, an arrival rate of 17.5 cards per hour. Three clerks serve at the ATCM and, based on internal estimates, each of them is able to process six cards per hour. This leads to a capacity utilization of 97 percent.

In a deterministic process, utilization lower than 100 percent indicates that the system has capacity to perform the tasks as they arrive, without delay. However, the capacity at the ATCM is probably overestimated, and the process is not deterministic. There is no indication that the capacity measured incorporates typical distractions that happen during the workday (interruptions, restroom breaks, etc.), which would lead the effective capacity to a number lower than six cards per hour. In fact, since the card processing is admittedly a tedious activity, it is likely that service times vary substantially from card to card and are probably exponentially distributed. Moreover, job arrivals are independent, and most independent arrival processes follow a Poisson distribution.

The combination of Poisson arrivals with exponential process times characterize a Markov process, meaning that substantial waiting lines are formed when capacity approaches 100 percent. In fact, Staffieri observed the development of large waiting lines. The backlog of cards to be processed at the ATCM program oscillated between 5,500 and 9,400 cards in a 6-month period, a backlog equivalent to 7.5–13 weeks of operation (Staffieri et al., 2009). Consequently, when an SRC card is missing, it may take a long time for the ATCM to determine if the part has any flight hours left and if it can be installed in the aircraft; it might well be that the most recent update on that individual part is among one of the thousands of cards in the backlog. Therefore, if a component is missing its SRC card, it may be several weeks before ATCM can provide an estimate of the number of flight hours remaining in the part, which of necessity will be sidelined until its status is clarified.

One solution to improving the CMIS/ATCM repository backlog would be to increase data entry capacity by adding another clerk to the system. The additional clerk will help reduce capacity utilization to just 73 percent. A simple illustration would be Markov's process wherein an hourly demand of 17.5 jobs and four servers with a capacity of 6.0 jobs would experience an average waiting line of about 4.2 cards, as shown in Table 2. However, it is possible that the effective capacity per clerk is lower than the estimated 6.0 cards/hr. As a result, the number of jobs waiting to be processed could be much larger, as shown by the examples in Table 2. If clerk capacity is too low, the system is unstable and the waiting line would increase indefinitely—a situation that we noticed at ATCM.

Adding a new clerk may contain the problem at CMIS/ATCM, but it does not address the missing SRC cards, a recurring issue that leads to grounded aircraft. Lost or inaccurate SRC cards can result in substantial part-life penalties that indirectly convert to dollars lost with the arbitrary reduction of the flight-hours remaining in the part that is missing the card. The problem stems from the lack of reliability of the card-based system. Moving to an automated PLM system would address these issues and help eliminate penalties that exist because of unreliable information management.

Figure 3 shows the potential benefits that may be derived from integrating the use of IUID with RFID to track components that exchange hands multiple times in their life cycle. These technologies provide



traceability, visibility, and automation with many positive consequences, as shown in Figures 1 and 2, leading to improved life-cycle tracking, increased capacity, and information reliability.

TABLE 2: EXPECTED NUMBER OF CARDS WAITING TO BE PROCESSED, AS A FUNCTION OF CAPACITY (DEMAND = 17.5 CARDS/HR)

		3 clerks	4 clerks
clerk capacity	3.8 cards/hr	n/a	n/a
	4.4 cards/hr	n/a	194 cards
	5.0 cards/hr	n/a	8.7 cards
	5.9 cards/hr	137 cards	4.4 cards
	6.0 cards/hr	39 cards	4.2 cards

The integration between IUID and RFID technologies takes the benefits further than either of the two can achieve acting alone: it provides sustained operational availability, which translates into more aircraft ready to fly. The unique identifier in each part would ensure its correct identification against a part life-cycle database, creating the right conditions for managing a maintenance history database. Moreover, the automation provided by the RFID technology would ensure that the data are accurately recorded and up-to-date.

Conclusions

We examined the issue of grounded aircraft due to misinformation regarding the availability of critical maintenance parts: the serially managed components. The Appendix describes the part-replacement process, indicating both the material and the information flow and exposing a weakness in the process: the potential that a component retrieved from replacement-parts inventory is missing a correct SRC card and, for this reason, cannot be installed in the aircraft. Unfortunately, that seems to be a common occurrence, for which the process designates a corrective action: obtain a new card from the data repository. The SRC card holds the history of the component; without it, using the component is not authorized, and aircraft may be grounded. Since the card replacement procedure may take 7-13 weeks, missing cards are a serious operational concern.

Many organizational issues can be addressed by implementing a combination of improvements in either a short or long time span, with costly or not-so-costly organizational reengineering. We propose two solutions: one low-cost remedial change, and a process redesign that requires substantial investment and broad commitment from all levels of leadership in the fleet, but that addresses the root of the problem.

Recommended Remedial Change with Immediate Impact

We have seen that the CMIS/ATCM Repository is understaffed, leading to almost 13 weeks of backlog, rendering customer service completely powerless to serve the maintenance officers in the aviation community. To meet the recurrent demand (without adding to the current backlog), it is necessary to increase the number of clerks maintaining the database. Considering the existing backlog, holidays, leaves, and other distractions that prevent any process from continually operating at full capacity, as well as the costly impact of not providing immediate response to maintenance officers, two clerks should be added to the standard staffing level at the database repository. Maintaining this resource level would prevent backlog build-up, a common phenomenon in services with high-capacity utilization and variable arrival and service rates.

Recommended Process Change with Permanent Impact

Increasing the staff level at the CMIS/ATCM Repository, however, is not the cure, just the palliative solution. It is important to consider the source of the problems—the SRC card itself. Figure 3 shows how the joint utilization of IUID and RFID can increase operational availability through traceability, visibility, and automation.

The U.S. Navy adopted the Optimized Organizational Maintenance Activity (OOMA), an automated system that provides maintenance officers with aircraft information on which to base daily decisions. Fortunately, both OOMA and the database software used by the CMIS/ATCM Repository have the ability to use UIIs as their primary aircraft-part identifier reference. Since the Department of Defense mandates that manufacturers mark serially managed items using UID technology, the U.S. Navy should accelerate the adoption of UID as the main aircraft-part identifier. These tags should be coupled with passive RFID to ensure timely and accurate recordkeeping, eliminating the number of instances in which a part that is believed to be RFI is of unknown quality because of the lack of reliable records.

Our discussion focused on the life-cycle management of aircraft components. The same concerns exist in the life-cycle management of other valuable assets, including ocean-going vessels, armored vehicles, off-road, mining, and other heavy-duty machinery. Managers should plan for life-cycle tracking of high-value moving assets using automated technologies. A combination of passive RFID and a 2-D barcode such as Data Matrix ECC200 seems to be the right solution for the problem.

Acknowledgments

The authors are grateful to LT Will Gray, USN, Aircraft Intermediate Maintenance Department, *USS Ronald Reagan*, for clarifying and validating the SRC card process; and to LCDR T. J. Staffieri, USN, School of Aviation Safety, Naval Air Station Pensacola, for the many discussions about the SRC card maintenance database at the CMIS/ATCM. This work was supported in part by the Acquisition Research Program of the Naval Postgraduate School under Project No. F09-035.

Author Biographies

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Dr. Geraldo Ferrer is an associate professor of Operations Management at the Naval Postgraduate School. His areas of expertise include global operations, supply chain tracking technologies, sustainable technologies, and reverse logistics—topics on which he has published numerous articles. He has also presented his research in national and international conferences, and in various invited seminars. Dr. Ferrer received his PhD from The European Institute of Business Administration (Institut Européen d'Administration Des Affaires–INSEAD), an MBA from Dartmouth College, and a BS in Mechanical Engineering from Instituto Militar de Engenharia (IME) in Rio de Janeiro.

(E-mail address: gferrer@nps.edu)



Dr. Aruna Apte is an assistant professor in the Graduate School of Business and Public Policy, at the Naval Postgraduate School, Monterey, California. Her current research interests include humanitarian and military logistics. She received her PhD in Operations Research from Southern Methodist University in Dallas, Texas.

(E-mail address: auapte@nps.edu)

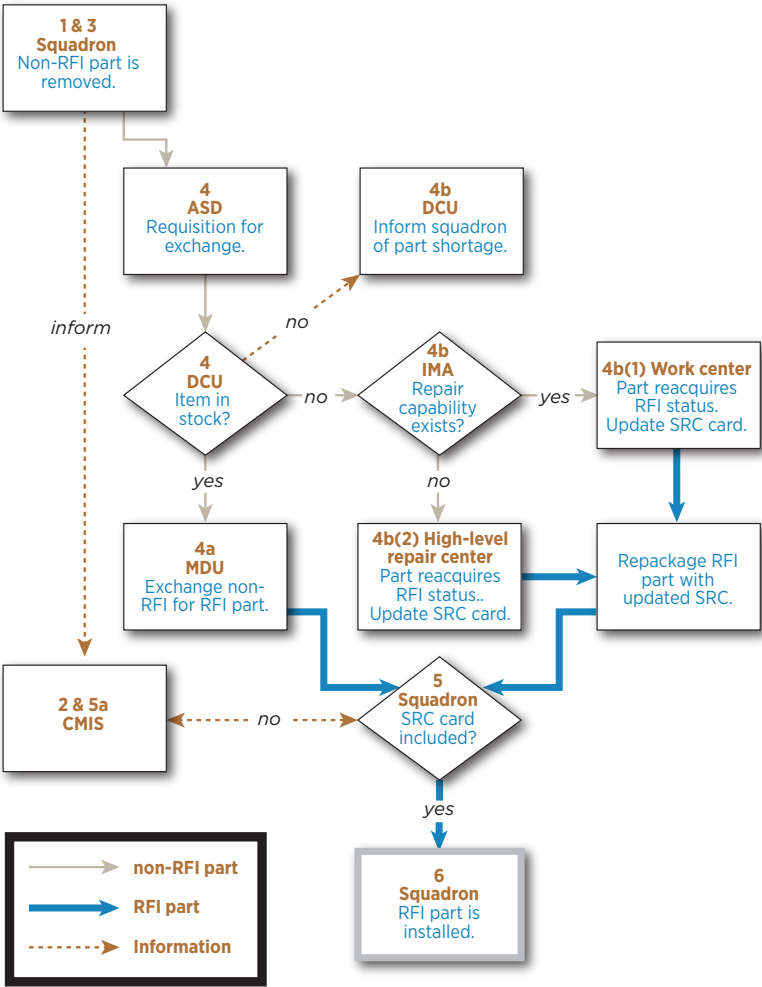
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Appendix

Process for Recreating a Scheduled Removal Component Card



1. The non-ready-for-issue part (non-RFI) is removed and its SRC card is updated with the new status.
2. A copy of the SRC card is sent to the Configuration Management Information System (CMIS), which keeps information on all serially controlled parts.

3. The updated SRC card is packaged with the corresponding non-RFI component to be exchanged for a ready-for-issue (RFI) component.
4. A requisition document for a replacement part is conveyed to the Aviation Support Division (ASD). The Document Control Unit (DCU) personnel process the request and determine if an RFI item is in stock.
 - a. If the RFI item is in stock, then the process moves to Material Delivery Unit (MDU). The MDU sends the RFI item to the squadron. The non-RFI part and its card are collected in exchange for the replacement RFI part.
 - b. If the RFI item is not available, then the squadron is informed. The SRC card of this non-RFI part is verified and updated. The non-RFI item is sent with its card to the Intermediate Maintenance Activity (IMA) facility for repair.
 - (1) If the IMA has repair capability and the part is not beyond the capability of maintenance, then a work center and work priority is assigned to the part by Production Control. The part is then transported to a work center, where it is repaired and receives RFI status.
 - (2) If the IMA work center does not have repair capability, then the part is sent to the next-higher-level repair facility, where it is repaired and receives RFI status.
5. The squadron receives the part, opens the package, and verifies if the SRC card is included.
 - a. If the SRC card for the part in inventory is missing, then the part is not used because the maintenance officer cannot establish the number of flight-hours that are still available in it or even if the part is RFI. The CMIS is contacted to re-create an SRC card with an estimated number of flight-hours that the part can still safely deliver. The squadron waits for confirmation
6. Once the SRC card is confirmed to be with the part, the card is updated and the part is installed in the aircraft.